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Model of Energy Storage Circuit for Isotope Battery Based on SiC Schottky Diode

by Robert Schmid, Yves Ngu, and Marc Litz

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Robert Schmid, Yves Ngu, and Marc Litz
Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

This study analyzes how to efficiently create a storage circuit to charge a capacitor with a radioisotope power converter. Variables analyzed include capacitance and frequency of pulse/discharge. Virtual Test Bed was used to display the transient effects of the charging circuit. MATLAB was used to explore the efficiency of circuits. Results indicate efficient circuits need a capacitance that correlates to the number of times the capacitor is discharged in a day.

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Contents

List of Figures

Introduction

Isotope batteries use radioisotope power converters to transform radiation into a useful form of electrical energy. One such radioisotope power converter is the SiC Schottky Diode. The radiation emitted from the isotope creates free electrons and holes in the SiC converter. The free electrons cross the diode junction which results in electrical flow through the load. The electrical energy is in the form of a small trickle current. This current can be used to charge a capacitor over time to create a significant amount of energy. There are many applications where it would be useful to have a long-lived battery that would create pulses a few times a day. For example, bridges often contain embedded sensors which collect information on the structural integrity of the bridge. Isotope batteries would be ideal for these applications because of their long life and reliability.

This research focuses on how to store the energy from a trickle current, to be used in a burst-mode circuit. A model of the equivalent circuit of the SiC Schottky Diode has been developed by Yves Ngu (*1*). The goal of this research will be to use the model of SiC Schottky Diode to develop an efficient circuit that stores the charge from the diode and can discharge a pulse of energy a few times a day.

Concept

A SiC Schottky Diode exposed to radiation has been proven to have the equivalent circuit shown in figure 1.

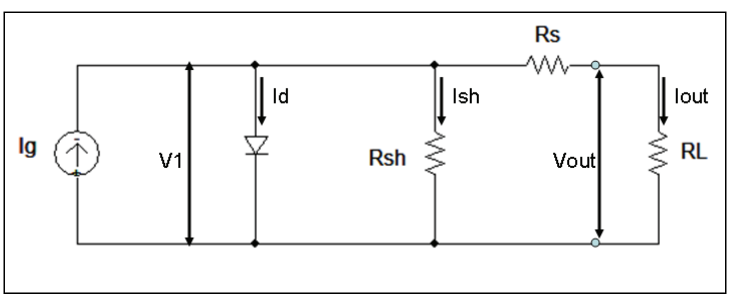

Figure 1. Yves Ngu's model of SiC Schottky Diode exposed to radiation (*1*).

To store the energy released by the diode, the load (RL in figure 1) was replaced with a capacitor. With the capacitor in place of the load, the circuit was then modeled in the Virtual Test Bed with the assumption that the diode was larger than the output voltage threshold (voltage drop over the diode was 0.6-0.7 volts). The Virtual Test Bed circuit and waveform are shown in

figures 2 and 3 respectively. In the Virtual Test Bed, programmable loads were used to model switches for charging and discharging. Also, note the current source has an internal parallel resistance of 7 MOhm to model the diode's shunt resistance (Rsh in figure1).

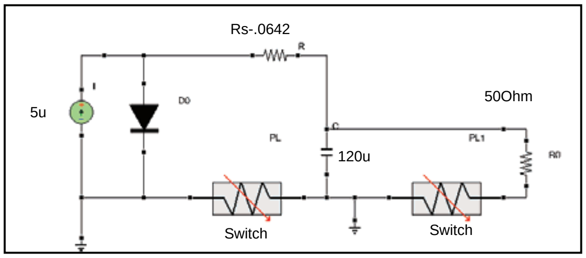

Figure 2. Virtual Test Bed Circuit.

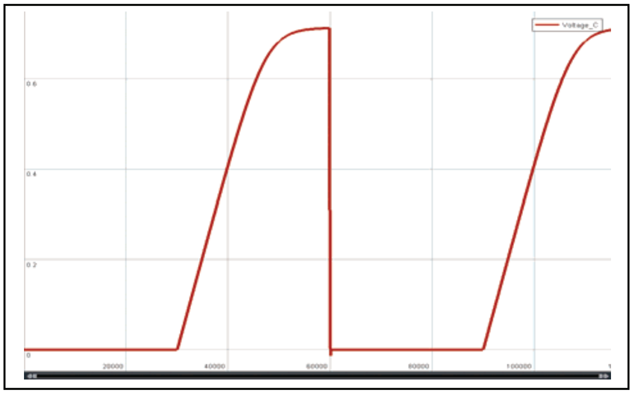

Figure 3. Waveform of voltage drop over capacitor.

The circuit was designed to have two main parts, a charging circuit and a discharge circuit. The charging circuit is the bigger loop on the left. When the switch on the left was closed and the switch on the right was opened, the capacitor would charge up and no charge would be released into the right loop. The right loop is the discharge circuit. After the capacitor was charged up, the switch on the left would be opened and the switch on the right would close. This would allow the charge in the capacitor to discharge over the resistor (R0). This circuit produced the wave form for the voltage drop over the capacitor seen in figure 3.

The waveform produced in the Virtual Test Bed appears to be similar to that produced by a simple circuit including a voltage source with a resistor and capacitor in series. To develop an equivalent circuit, three values are needed: the value of the voltage source, the capacitance and the equivalent resistance. In this case, the voltage source would equal the maximum voltage. Since series resistance (Rs) and the capacitor are in a branch that is in parallel with the diode, the voltage over the capacitor will approach 0.7 V. Thus, the voltage source should have a value of 0.7 V. The capacitance in the equivalent circuit will be the same as the original circuit. Resistance is the only value that remains to be determined.

To solve for R we used the wave form in figure 3. The waveform was analyzed to find how long it took the capacitor to reach 63% of its maximum voltage. Based on the charging equation for a capacitor (1), when the voltage reaches 63% of its maximum, it is at one time constant or T=RC.

$$V = Vin(1 - e^{t/RC}) \tag{1}$$

The time and capacitance can then be used to solve for resistance. The consistency of the resistance value was checked by testing various levels of capacitance and recording the time of one time constant. We then plotted this data, seen in figure 4, and the derivative was taken to approximate resistance.

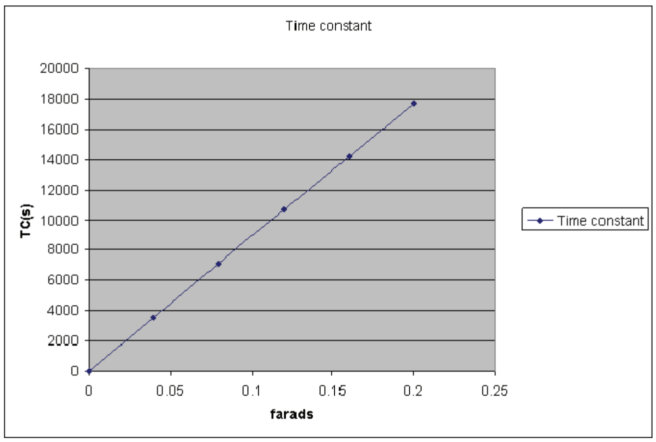

Figure 4. Capacitance versus time constant. The slope is the resistance (approximately 88,437.5 Ohms).

Now that the equivalent resistance for the circuit has been determined, an equivalent circuit (seen in figure 5) can be created. This circuit is much easier to work with and the energy stored in the capacitor can now easily be analyzed by equations 1 and 2.

$$E = \tfrac{1}{2}CV^2 \tag{2}$$

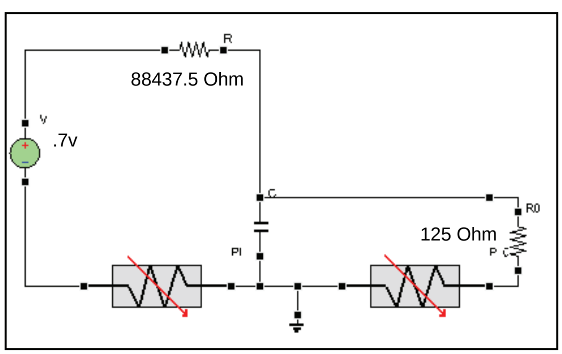

Figure 5. Equivalent charging circuit.

MATLAB Analysis

MATLAB[1] provided an essential tool in analyzing a variety of aspects of the storage circuit. Based on the simple charging circuit in figure 5, MATLAB was used to graph total energy versus time. This graph combined both equations 1 and 2, taking into consideration the capacitor may charge more than once in a certain time period. Figure 6 shows the graph of total energy versus time. In this figure, the capacitor is repeatedly charged up for 300 seconds and then discharged. The discharge time is ignored in this model because it is very small compared to the charging time. After the capacitor is discharged, it begins charging again. The term "total energy" refers to all the energy that the capacitor absorbed from the diode up to that point in time. This value is significant because it is important to maximize the amount of energy the capacitor is collecting from the diode.

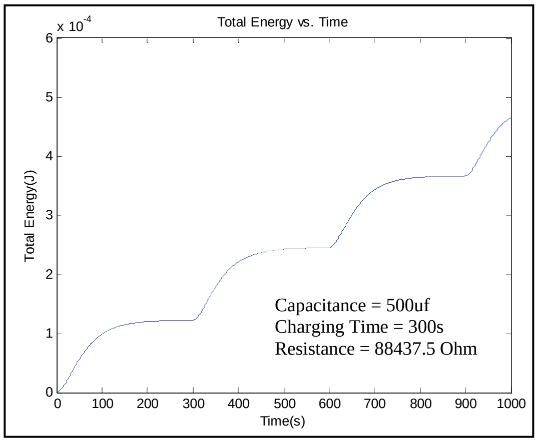

Figure 6. Total Energy versus time.

Since the total energy is important in determining efficiency of the circuit, it is important to maximize this value based on the capacitance and charging time. Figure 7 indicates how the total energy changes with capacitance and charging time. In this figure total energy represents the total energy absorbed by the capacitor through 10 hrs. Clearly, total energy does not always increase with capacitance. Rather, capacitance must be chosen based on the charging time in order to maximize efficiency of the circuit. Also, total energy increases with charging time. However, when the charging time is increased, the capacitor cannot be discharged/pulsed as often.

[1]MATLAB is a registered trademark of The MathWorks.

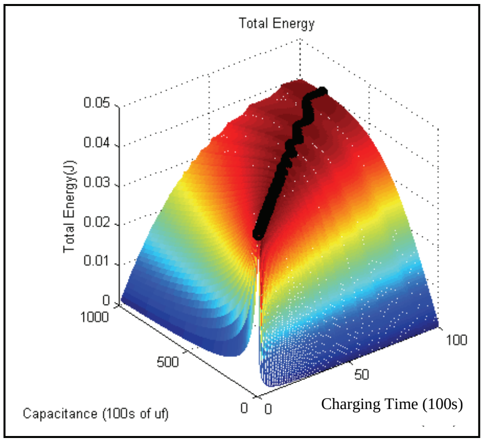

Figure 7. Total energy versus charging time versus capacitance for 10 hrs.

Recall that the intended application of the storage circuit is to release a small pulse a few times a day. The goal is to make that pulse as large as possible given the number of times a day the capacitor needs to releases a pulse. Now compare figures 6 and 8. Although figure 6 has a significantly larger total energy after 1000 seconds, the amount of energy it would give off in one pulse (look at the end of the first charging cycle) is slightly less than figure 8. In figure 6, when that fourth charging cycle is started, the total energy increases very quickly in the beginning of the cycle. This also explains the ripples seen as charging time increase in figure 7.

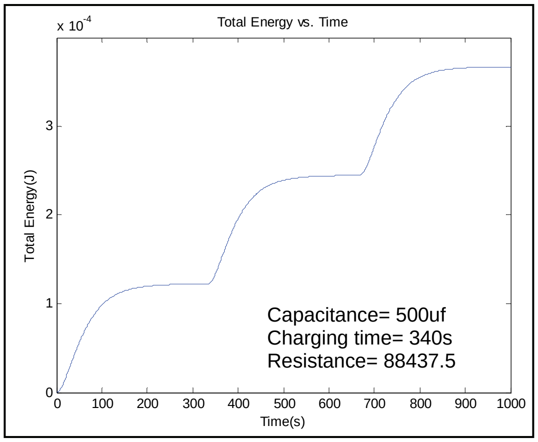

Figure 8. Total energy versus time (340s charging time).

In an application where a capacitor would pulse a fixed number of times per day, it is actually the energy per pulse that should be maximized and not the total energy. With this in mind, the capacitor was analyzed in terms of energy per pulse. Figure 9 displays a graph of Energy Per Pulse versus Pulses Per Day versus Capacitance. Pulses Per Day is just another measure of the charging time, but the data in a more tangible form. The pulses per day are calculated by dividing the seconds in a day by the charging time.

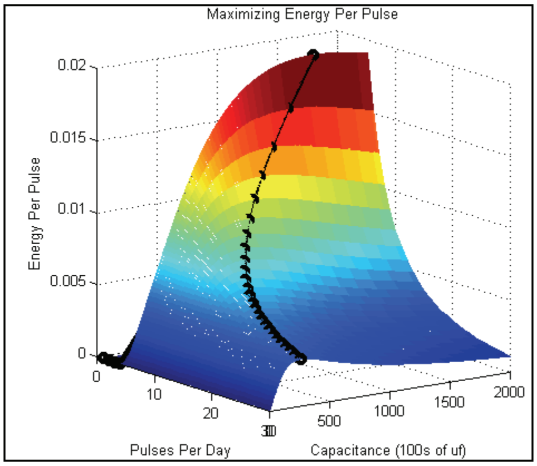

Figure 9. Energy per pulse versus pulses per day versus capacitance.

Figure 9 ranges from 5 to 30 pulses per day. Data can be collected beyond this range. However, as the pulses per day approach closer to zero, the energy per pulse increases dramatically and it is harder to see the shape of the graph. The black line indicates the maximum energy per pulse for a given number of pulses or capacitance. Thus, if a particular device called for 6 pulses a day the graph could be used to find the capacitance at which the energy per pulse would maximize and what the energy per pulse would be.

Future Research

The next step of this study will be to apply these forms of analysis to parameters closer to that of SiC Schottky diodes used for isotope batteries. This study assumed that the diode generated a voltage that exceeded the capacitor voltage threshold. It was assumed that the voltage drop over the diode was 0.6-0.7v regardless of the current going through the diode. Unfortunately, when the SiC Schottky diodes are used for isotope batteries this is not true. The current going through the diode is in the nano-Amp range. Referring to figure 10 (*2*), it is clear that at low currents the voltage over the diode is not fixed, but actually dependent on the current.

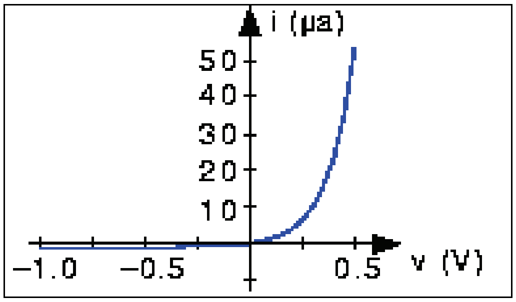

Figure 10. Voltage-Current relationship of a diode (*2*).

Thus, to apply the parameters of the isotope battery, the voltage cannot be assumed to be 0.6-0.7 regardless of the current. The relationship of current and voltage over the diode must be included in the model. Research on a similar circuit (figure 11) by Adelmo Conde (*3*) has found:

$$I = \frac{\eta V_T}{R_S} W\left\{ \frac{I_0 R_S R_{P1}}{\eta V_T (R_{P1} + R_S)} \exp\left[\frac{R_{P1}(V + I_0 R_S)}{\eta V_T (R_{P1} + R_S)} \right] \right\} + \left(\frac{V - I_0 R_{P1}}{R_{P1} + R_S} \right),$$

$$V = I(R_{P1} + R_S) + I_0 R_{P1} - \eta V_T W\left\{ \frac{I_0 R_{P1}}{\eta V_T} \exp\left[\frac{(I + I_0) R_{P1}}{\eta V_T} \right] \right\}.$$

Where Io is the junction reverse current, Vt is the thermal voltage and n is the ideality factor. Conde uses the W-function to solve explicitly for current and voltage. Similar methods may be used for the model of SiC Schottky Diode exposed to radiation.

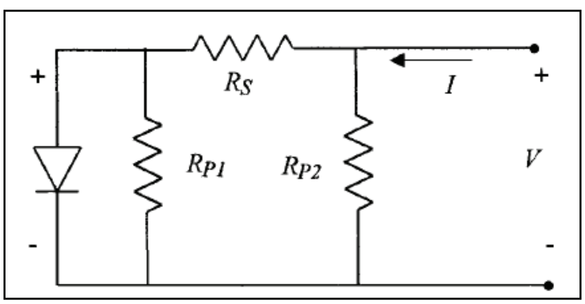

Figure 11. Conde's model of non-ideal diode (*3*).

Even with an accurate formula for the current and voltage over the diode it will be hard to determine exactly how the capacitor will charge. To understand this, refer back to figure 1 and replace the load with a capacitor. Ig, the current source will provide a relatively constant current. Some of this current will go through the diode, while some of the current will go to the capacitor. As the capacitor charges up, how the current is distributed between the capacitor and the diode will change. This means the current going through the diode will change. Remember, the

current is in the nano-Amp range and the voltage over the diode is dependent on the current. Thus, because the current is changing, the voltage over the diode will change. Finally, since the voltage over the diode is acting as the applied voltage to the capacitor, this means the capacitor is charging up with a varying applied voltage. The challenge of this next step of the investigation will be in determining how the capacitor will charge up with a varying applied voltage and whether the circuit can be simplified.

Capacitor Types

Although research on storage circuits for isotope batteries is far from finished, a few characteristics about these capacitors in these circuits are clear. First, looking at figure 9 it is clear the capacitance will need to be large, on the order of mf and possibly up to the farad range. Also, the capacitor should be able to discharge quickly in order to quickly send out a pulse a few times a day. In addition, the capacitor should be able withstand years of charging and discharging because the isotope batteries will be producing a small trickle current for decades.

There are three main types of capacitors: electrostatic, electrolytic, and electrochemical. Electrostatic capacitors store energy between two plates with an insulating material in between. Electrolytic capacitors have two plates and an electrolyte between the plates. The conductivity of the electrolyte allows the electrolytic capacitor to achieve higher capacitances than electrostatic capacitors. Electrochemical capacitors have two plates and when a voltage is applied over the capacitor an electrolytic layer forms between the plates. For this reason electrolytic capacitors are often known as double layer capacitors. The double layer feature of the electrochemical capacitors allow for extremely large values of capacitance (*5*).

Electrostatic capacitors are not suitable for isotope battery applications because they cannot reach high enough capacitances. Electrostatic capacitors are normally used in the range of pico-farads and microfarads. While electrolytic capacitors have ideal discharging capabilities and extremely long life spans, their abilities in isotope battery application are also limited by their lower than practical capacitance values. Electrolytic capacitors can reach up into the range of millifarads, but they are very expensive.

Electrochemical capacitors or super capacitors are the ideal capacitor for isotope battery applications. Electrochemical capacitors are half-way between batteries and electrolytic/electrostatic capacitors (see figure 12 (*4*)). Unlike batteries, electrochemical capacitors are capable of withstanding hundreds of thousands of charging cycles like electrolytic capacitors. In addition, electrochemical capacitors are capable of storing more energy than electrolytic and electrostatic capacitors. Batteries normally discharge and charge in the range of minutes and hours. Electrochemical capacitors are able to discharge in the range of nanoseconds

to seconds. They are typically rated for temperatures between –40 °C and 60 °C. Finally, electrochemical capacitors are cheap for the level of capacitance. They cost approximately $1-$20/f. The only negative factor to electrochemical capacitors is that they have a slightly higher equivalent series resistance (ESR) than electrolytic capacitors. This is the reason electrochemical capacitors discharge slightly slower than electrolytic capacitors (*5*). Thus, electrochemical capacitors will be a good fit for isotope batteries.

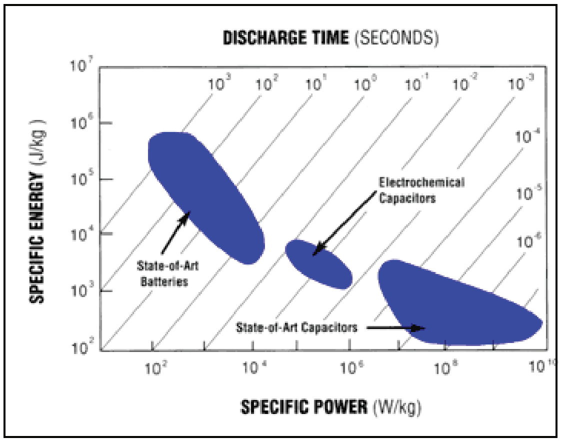

Figure 12. Differences between batteries, electrochemical capacitors and electrolytic/electrostatic capacitors (*4*).

Conclusion

Isotope batteries are currently being studied for applications in long life sensors. However, to make the isotope battery useful, an efficient way to store and discharge the energy must be developed. Developing an efficient storage circuit for isotope batteries will involve research on the nano-Amp scale focused on how a capacitor charges in parallel with a diode. To maximize the energy per pulse, the size of the capacitor will need to be determined based on the number of pulses per day it needs to deliver. Electrochemical capacitors have the ideal characteristics for such applications.

For a sensor application that required a reporting frequency of 6 times per day, the results of our investigation show that a low voltage, 1.5 mF electrochemical capacitor should be used to efficiently make use of the ~1 mJ of energy available from the isotope battery.

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